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1 Introduction

§ 1.1 Energy consumption in the built environment

The rapid growth of urban areas has led to the unsustainable use of resources (Langeweg et al. 2000; Bhatta 2010; UN 2014). The impacts of urban areas are evident in regions which supply cities with food, water, energy and absorb pollution and waste (UN 2014). At the same time, the current world population, of 7.6 billion, is predicted to reach 8.6 billion in 2030 and 9.8 billion in 2050 (UN 2017). Moreover, the urban population, in 2014, accounted for 54% of the total global population. This signifies a 20% increase since 1960. In 2014, the majority of people - 54% - were living in urban areas and this percentage is estimated to rise in the future (WHO 2017). In Europe, 72.5 % of European Union (EU)-28 countries inhabitants lived in cities, towns and suburbs in 2014 (Eurostat 2016b). Nevertheless, differences between countries exist. Figure 1.1 shows the urban population growth of the Netherlands in comparison to the EU, Germany, Spain, France, Slovenia and Sweden. The Netherlands is characterised by a high level of population density and a high share of urban land use, whereas in most of the Scandinavian countries and Spain much lower levels of urban land use are present (Eurostat 2016b).

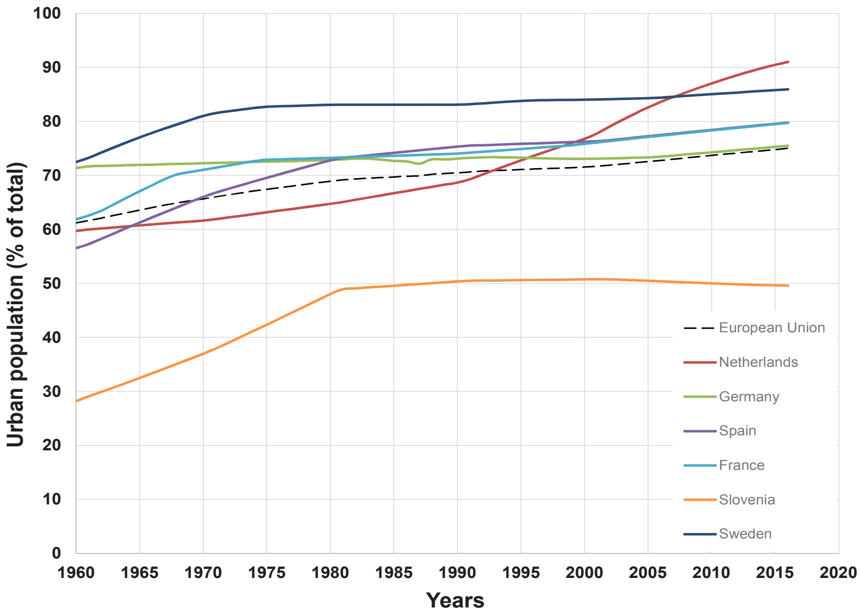

FIGURE 1.1 Examples of urban population as a percentage of the total population, in Europe, based on World Bank statistics 1960 – 2016 (source: The World Bank 2017)

In this context, the main challenge is to accommodate a greater number of people while reducing the impacts on the environment, which are the main cause for climate change (IPCC 2014). Relatedly, the improvement of the quality of life of city residents is a priority (EEA 2015). Households have a large impact on energy intensity and final energy consumption, as Figure 1.2 shows. The energy intensity[3] of households, depicted on the left hand side of Figure 1.2, is increasing and at the same time 25.4% of the final energy consumption in the EU 28 was attributed to the sector in 2015 (24.8% in 2016), shown on the right hand side of Figure 1.2 (EEA 2013; Eurostat 2016a). The potential for energy consumption reduction of households is large and is set as a key priority in the policy goals and directives by the European Commission (Paulou et al. 2014; Saheb et al. 2015). One of the most prominent ways to reduce the energy consumption of residential dwellings is through energy renovations.

3 Energy intensity is is expressed as the ratio between gross inland energy consumption and GDP, in a calendar year. To make comparisons across countries possible, the indicator is presented as an index, compared to 1990. (EEA 2013)

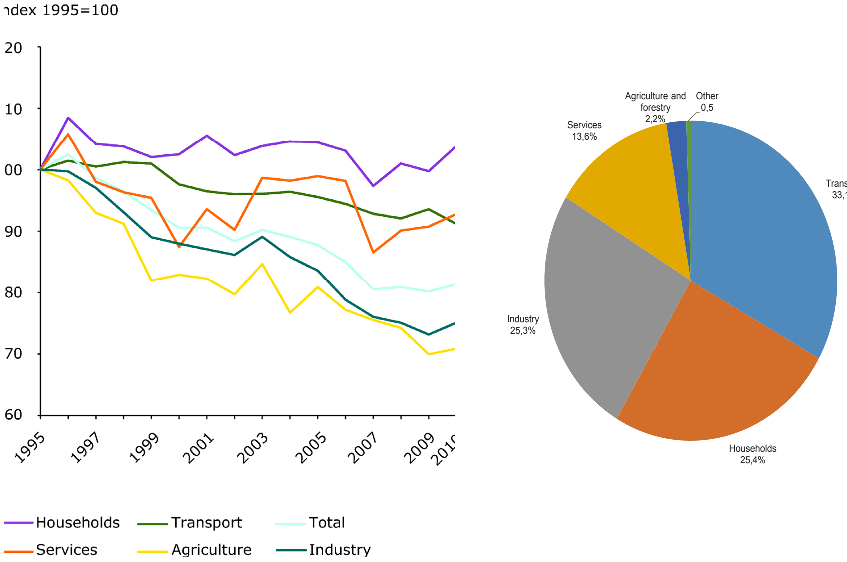

FIGURE 1.2 Energy consumption intensity and final energy consumption per sector in the EU 28 (sources: EEA 2013 and Eurostat 2016a)

§ 1.2 Energy efficiency and renovations

Energy efficiency, of buildings, is a topic where several definitions can apply. It is often misunderstood as energy conservation. *Energy efficiency* of a dwelling or building refers to its energy performance through its physical properties, energy installations, appliances and occupant behaviour (EIA 2016). The energy efficiency of a dwelling is the combination of the thermodynamic approach[4] of thermal efficiency and energy consumption intensity (Tanaka 2008). Whereas, *energy conservation* refers to less heating or less use of electronic devices, leading to a reduced energy consumption in total – it relates mostly to occupant behaviour (EIA 2016).

The energy performance of buildings is generally insufficient and the levels of energy consumed in them place the sector among the most significant CO_2 emission sources

4 Thermal efficiency is the term used in thermodynamics that measures the ratio of heat and/or work to the energy input. The maximum efficiency is 1 (100%) as defined by the second law of thermodynamics.

in Europe – 33% of the total final energy is consumed in buildings (BPIE 2011). A considerable percentage of this energy consumption is attributed to the residential sector, as on average dwellings are responsible for 24.8% of the total energy consumption in the EU (Eurostat 2016a). The energy savings potential of existing dwellings is expected to be large.

To cope with the issues at hand, the EU has set policy targets and regulations to ensure the energy efficiency improvement of the building stock. Apart from the general roadmap to emission neutrality of the building stock by 2050, the Energy Performance of Buildings Directive ([EPBD] 2002, recast 2010, European Commission 2016) is the main legislative and policy tool in EU and focuses on both new and existing buildings. At the same time, the building sector plays a prominent role in the Energy Efficiency Directive ([EED] European Parliament 2012). In 2008, the EPBD was applied, setting the goals for the built environment higher. Under this directive, all Member States must establish and apply minimum energy performance requirements for new buildings, for major renovation of buildings and for replacement or retrofit of building elements (heating and cooling systems, roofs, walls, etc.). The revised EPBD requires Member States to also guarantee that by the end of 2020, all new buildings are 'nearly zero-energy buildings' (Beuken 2012; van Eck 2015).

In the Netherlands several policy measures have been in place since the last quarter of the 20th century, mainly through building decrees. The energy consumption of buildings has been regulated since 1975 consisting of limits on transmission losses based on insulation values (Boot. 2009). In 1995 these limits were expanded to include the national "EPC" (Energy Performance Coefficient) which is a non-dimensional figure that expresses the energy performance of a building depending on the energy consumed for space heating, hot water, lighting, ventilation, humidification and cooling. In addition, in 2008, the EPBD is applied, setting the sets of goals for the built environment high. New buildings and major renovations in the Netherlands are required to meet specific standards e.g. R_c values of floors, facades, roofs and U values of windows, as of January 2015 (van Eck 2015). The majority of policy measures focus on the energy efficiency of buildings and the energy neutrality of new buildings. However, the realization of energy efficient measures or energy renovations of the dwellings could go even further and achieve the ambitious goals set on a national and European level.

Energy neutrality of the building stock is hard to achieve relying only on newly built dwellings. Existing buildings will dominate the housing stock for the next 50 years based on their life cycle; in the Netherlands, the annual rate of newly built buildings is 0.6% of the existing residential building stock in 2014 (Statistics Netherlands 2015). Therefore, renovation activity is expected to be greater than construction and demolition activity in the future. Renovations offer unique opportunities for reducing energy consumption and greenhouse gas emissions, and are instrumental for reaching the EU 2020/2030/2050 goals (Saheb et al. 2015). This has implications for growth and jobs, energy and climate, and cohesion policies (Paulou et al. 2014 and Saheb et al. 2015). Renovating existing buildings is seen as a 'win-win' option for the EU economy (Saheb et al. 2015). While there have been various energy renovations of dwellings in Europe, the assessment and monitoring of these renovations is limited (Hamilton et al. 2017; Dascalaki et al. 2016; Droutsa et al. 2016; Corrado & Balarini 2016).

Though there is a great deal of research on the energy efficiency and energy consumption of the housing stock, little has been published on the rate of improvement and the impact of energy renovations on actual energy consumption. And even though the energy efficiency policies and initiatives implemented in the Netherlands make it an ambitious goal-setter in the EU residential sector, there is no evidence of a steady reduction of gas and electricity consumption compared to the 1990 levels (Majcen et al. 2013). On the contrary, the total energy (gas and electricity) consumed by households increased by 11% from 1990 to 2008 (Majcen et al. 2013). Furthermore, the rate of renovations and the amount of energy savings achieved are essential to reach the ambitious goals set on a national and European level. It is critical to attain insight into whether these goals can be achieved. There are contradicting studies: some argue that the goals are reachable, and others mention that any progress is based on estimated values of energy consumption so the realization could be much more difficult (Balaras et al. 2016; Majcen et al. 2013; Sunikka-Blank & Galvin 2012).

§ 1.3 Non-profit housing

The tenure mix of dwellings bears a significant relevance to the ability to renovate. The total amount of dwellings in the Netherlands is 7.5 million (BZK 2016b). The owner occupied sector comprises 55.8% of the total, whereas the rental sector amounts to 43.5% (BZK 2016b). The ownership type is unknown for the remaining 0.7% (BZK 2016b). The vast majority of the rental sector belongs to housing associations forming the non-profit housing sector. In this dissertation, we focus on the Dutch non-profit housing because the sector comprises approximately 2.3 million homes, which adds up to 30% of the total housing market (BZK 2016a). This is a unique situation, as the Netherlands have the highest percentage of non-profit housing in the EU (Braga & Palvarini 2013). The non-profit housing sector can be expected to be a leading example when it comes to energy efficiency goals due to its intrinsic social values and different organization and behaviour from the private sector. It is considered as a service of general economic interest by the EU due to the fact that it can ensure the right to housing and be a key player in achieving the Europe 2020/2030/2050 targets (Braga & Palvarini 2013).

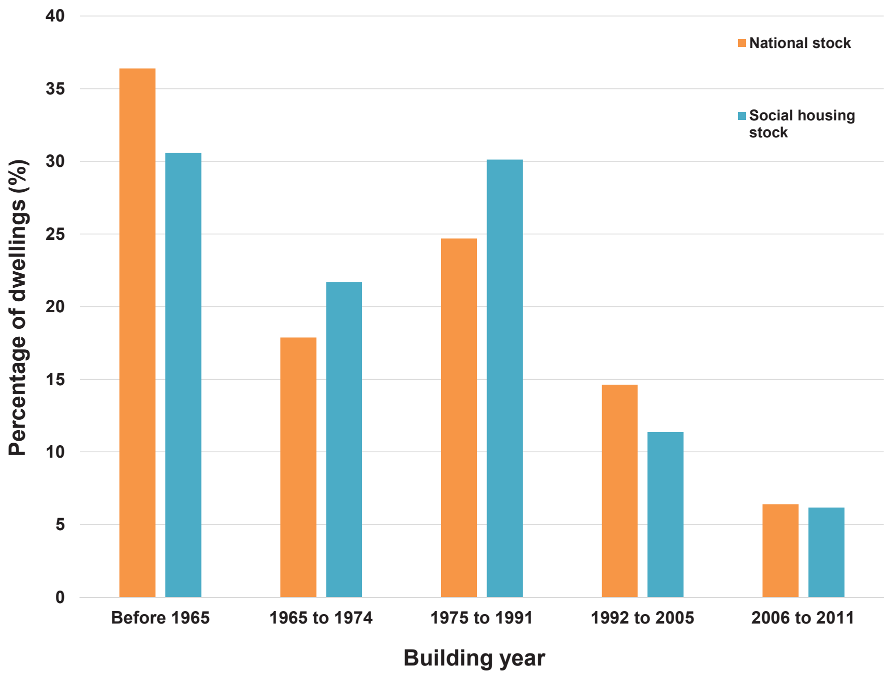

FIGURE 1.3 Comparison of building year cohorts distribution between the national and social housing stock. (source: Agentschap NL 2011 and SHAERE database)

Non-profit housing is typically owned by the public sector; however, there is an increasing trend towards non-public involvement or the privatization of the non-profit housing sector in Europe (Braga & Palavarini 2013). Since the beginning of the 1990s the Dutch non-profit housing sector deviated from government control and public financing and became a financially independent sector. In the Netherlands, non-profit housing is almost entirely in the hands of private organisations (Elsinga & Wassenberg 2014; Priemus 2013; BPIE 2011; Kemeny 2002). These organizations can be better described as “hybrid” – they act between government, market and community (Nieboer & Gruis 2016). They have to manage the different and frequently competing interests from each of these three entities (Nieboer & Gruis 2016). The housing organizations have to fulfil several mandatory goals regarding the provision and allocation of homes.

For this thesis, we consider the non-profit rented housing stock of the Netherlands, also referred to as social housing, where a significant amount of data are available, for two main reasons. First, the non-profit housing sector in the Netherlands is the largest in Europe, having a share of 31% of the total stock. We use a newly formed source of data that includes 60% of the dwellings in the sector. This fact advances the research, providing the opportunity to work on a representative sample of the national housing stock, in terms of construction but necessarily typology (see Figures 1.3 & 1.4). Having such an extensive and representative sample of dwellings is a stepping stone for the provision of statistically significant results. Second, the non-profit housing sector is making decisions about energy efficiency and sustainable solutions collectively and is being subsidised by the state for goals promoting the energy neutrality of the country.

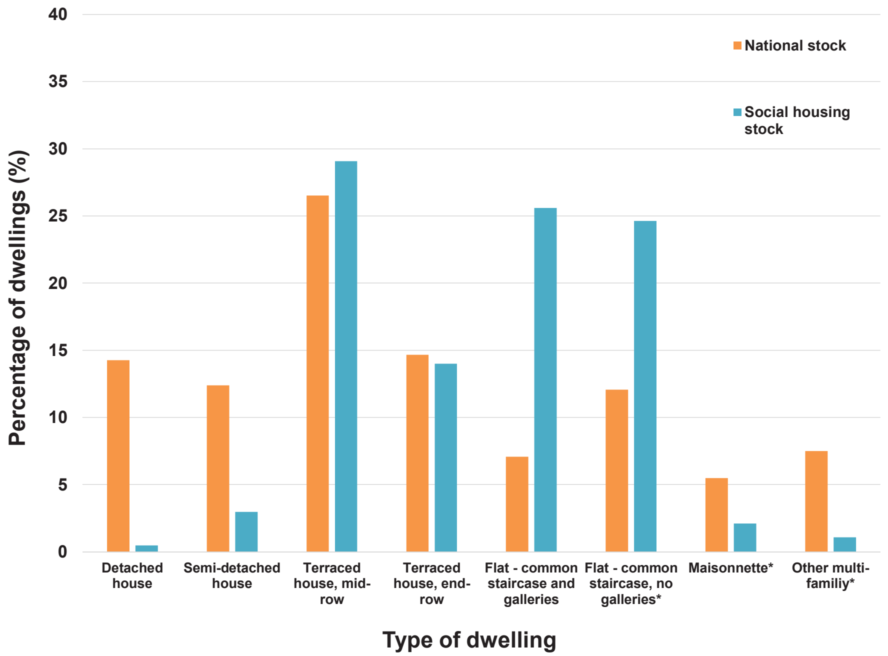

FIGURE 1.4 Comparison of type of dwelling cohorts' distribution between the national and social housing stock. (source: Agentschap NL 2011 and SHAERE database)

Energy savings and sustainability are high on the housing associations' agenda, especially since 2008, when the EPBD started being implemented (Aedes 2018). According to the Energy Saving Covenant for the Rental Sector ("Convenant Energiebesparing Huursector"), the current aim of the non-profit housing sector is to achieve an average EI (Energy Index - Dutch energy performance coefficient for existing dwellings) of 1.25 by the end of 2020 (BZK 2014), which is within the bands of an energy label B. The Covenant was signed by, among other stakeholders, Aedes (the umbrella organisation of housing associations), the national tenants' union and the national government. The goal of the agreement means an energy saving of 33% on the theoretical/predicted energy consumption in the period of 2008 to 2021 (CECODHAS Housing Europe 2012).

§ 1.4 Problem definition and aim of thesis

There is a present need to research the energy renovation practice and progress of energy performance in the existing housing stock. Monitoring is essential and can provide valuable information concerning the energy savings that can be achieved, in terms of both actual and predicted energy consumption. The predicted energy reduction, in most cases, differs from the actual energy consumption (Filippidou et al. 2016; Balaras et al. 2016; Majcen et al. 2013, Tigchelaar et al. 2011). The mean predicted or modelled energy consumption in dwellings can be as much as 50% less or 30% more than the actual consumption (Majcen et al. 2016). Moreover, previous research (Balaras et al. 2016; Majcen et al. 2013; Sunikka-Blank & Galvin 2012) has highlighted the performance gap – the difference between predicted and actual energy consumption – in different building stocks. Therefore, the focus on actual consumption is increasing, and studies of the gap between the predicted and actual energy consumption of buildings have started to appear in Europe.

The aim of the current research is to examine the progress of the energy performance towards emission neutrality, in the existing housing stock, through the application of energy renovations. To do so, we analyse, first, the energy efficiency state of the stock. Furthermore, we assess the type of energy renovations, their pace and their impact on the energy performance and the actual energy savings. In other words, we provide insight into the effect that the thermo-physical characteristics of dwellings have on efforts to make the existing housing stock emission-neutral.

§ 1.5 Research questions

In this section we introduce the main research question and the four subsequent questions defined for this research study:

What is the energy efficiency progress of the non-profit housing stock, through energy renovations, and what is their impact on the actual energy consumption?

The sub-questions are formed as follows:

1 How efficient is the Dutch housing stock in terms of energy performance?
The first research question aims to ascertain the current energy performance state of the Dutch non-profit housing stock. We approach the efficiency of the stock in 2015, in terms of descriptive statistics of the main elements of thermo-physical, dwelling characteristics, installations, modelled and actual energy consumption. It is important to understand the efficiency state of the stock in order to further examine the process of energy renovations and their effect on the buildings' performance and final energy consumption. The research question can be broken down into the following sub-questions:

- a What are the insulation levels of the envelope? (Chapter 2)
- b Which are the most frequent installations – space heating, domestic hot water and ventilation? (Chapter 2)
- c What is the modelled and actual final energy consumption? (Chapter 2)

2 What is the energy renovation rate of the housing stock?
Understanding the pace at which energy renovations are realised is of great importance to the implementation of energy efficiency policies in the built environment. Question 2 follows up on the energy efficiency state established in Chapter 2. We aim to determine the actual renovation rate of the non-profit housing stock in order to conclude if the targets set are reachable and if not, what are the policy instruments needed to increase this rate. Four sub-questions derive from research question 2:

- a Are the energy efficiency targets of the non-profit housing stock reachable? (Chapter 3)
- b What are the lessons learned from the policies applied in the sector and their implementation progress? (Chapter 3)

3 What are the energy efficiency measures realised the last years?
Energy renovations in existing dwellings offer unique opportunities for reducing the energy consumption and greenhouse gas emissions on a national scale in the

Netherlands but also on a European and global level. Although there have been initiatives for energy renovations of dwellings in the Netherlands, the assessment and monitoring of these renovations has been lacking. Monitoring the energy improvements of the existing housing stock is necessary and can provide valuable information concerning the technical characteristics and the future potential of the measures applied. We reply to this question by investigating what the energy improvement measures in the Dutch non-profit housing sector are over the last years and how they impact the energy performance of the dwellings. The sub-questions are:

a Are the envelope elements and installations being renovated at the same frequency? (Chapter 4)
b Are energy renovations being realized as single measures or combinations? (Chapter 4)

4 What is the impact of the energy renovations on the actual gas consumption savings? Usually, the energy savings are based on modelling calculations. However, recent research has shown that the predicted energy consumption differs largely from the actual consumption (Balaras et al. 2016; Majcen et al. 2013; Sunikka-Blank & Galvin 2012). In order to set realistic goals for energy efficiency and policies that deliver the results needed it is significant to understand the actual savings that are achieved by renovating the existing housing stock. Answering the above mentioned research question, we re-assess the effectiveness of energy efficiency measures based on actual consumption data through time series statistical modelling. The last sub-questions are:

a What is the difference between predicted and actual energy consumption savings of the renovated dwellings? (Chapter 5)
b Which are the most frequent combinations of energy efficiency measures? (Chapter 5)
c What is the effect of the different energy savings measures on the predicted and actual the savings? (Chapter 5)

5 What is the predicted energy renovation rate of the stock up to 2050?
The rate at which energy renovations are realized and the energy performance level achieved after the renovations are crucial factors for an energy-efficient built environment, as stated in Chapter 3. Energy renovation rates assumed by EU officials and policy makers usually range from 2.5-3% (BPIE 2011; Sandberg et al. 2016;). However, at current rates it is claimed that more than 100 years will be needed to renovate the EU building stock (European Commission 2016). The main question addressed in Chapter 6 is what the estimated renovation rates for the Dutch non-profit housing stock are for different types of renovations, depending on the level of

renovation and energy saving measures applied. Answering this question can help evaluate current and previous policies but also shape future ones.

a. What methods can be used to accurately predict energy renovation rates? (Chapter 6)
b. How do predicted energy renovation rates compare to empirically calculated rates? (Chapter 6)

§ 1.6 Data and methods

Approaches to monitor the building stock have evolved separately across countries in Europe. Information about the progress of energy performance renovations is necessary to track the progress of policy implementation and its effectiveness. Moreover, advanced quality information and data are needed to help develop roadmaps and future policies resulting in energy efficient buildings. To this day, each country is gathering and analysing data for the development of their building stocks individually and in a different manner. Some collect data through the Energy Performance Certificates (EPCs) databases and others perform housing surveys in representative samples (Filippidou et al. 2017). In some cases, information gained through the investments on energy renovations are used to calculate the progress.

As mentioned beforehand, for this thesis, we consider the non-profit rented housing stock of the Netherlands, also referred to as social housing, where a significant amount of data are available. Through empirical data and a synthesis of methods, we are able to provide new results regarding the progress of energy renovations in the existing housing stock. In 2008, after the formulation of the Covenant on energy saving targets, Aedes started a monitoring system of the dwellings called Sociale Huursector Audit en Evaluatie van Resultaten Energiebesparing (Social Rented Sector Audit and Evaluation of Energy Saving Results) abbreviated SHAERE. This monitor became operational in 2010 and contains information about the energy performance of around 60% of the Dutch non-profit housing sector (circa 1.2 million dwellings). Housing associations report their stock to Aedes at the beginning of each calendar year accounting for the previous year (e.g., in January 2014 reporting for 2013) (Aedes 2018). They report the energy status of their whole dwelling stock, every year, using the Vabi Assets software, whose basis is the Dutch energy labelling methodology (ISSO 2009). As a result, SHAERE consists of the actual characteristics of all dwellings of the participating housing associations at the end of each calendar year. SHAERE is the first monitoring database of the energy efficiency evolution of the building stock in the Netherlands with microdata information, on a dwelling level. We connect each record to the specific dwelling, it refers to, based on an encrypted identifier variable (dwelling ID) that consists of the dwelling's post code, address, number and possible number addition. It is a time series database including a maximum of five records per dwelling – 2010, 2011, 2012, 2013 and 2014. Table 1.1 shows an example of the structure of the database connecting the dwelling ID with the Rc for roof variable. In the same manner all available variables are connected to each dwelling based on the ID.

TABLE 1.1 Example of the structure of SHAERE (variables dwelling ID and Rc-value roof)

DWELLING ID	R_c-ROOF.2010 [m²K/W]	R_c-ROOF.2011 [m²K/W]	R_c-ROOF.2012 [m²K/W]	R_c-ROOF.2013 [m²K/W]	R_c-ROOF.2014 [m²K/W]
#1	0.6	1.1	1.1	1.1	1.1
#2	0.9	2.3	-	2.3	2.3
#3	-	-	3.1	-	3.1
...	...	...	...	...	...

The database includes data from 2010, 2011, 2012, 2013 and 2014, on the performance of the stock in the form of energy certificates. The data comprise of physical characteristics (thermal transmittance [U-value] and resistance [Rc-value] values of the envelope elements, the typology of dwellings, the year of construction, etc.), heating and ventilation installations, theoretical energy consumption[5], CO_2 emissions, the average EI and more (Filippidou et al., 2016). The variables are categorized per dwelling. A considerable part of the non-profit housing stock is included in SHAERE. However, the number of homes differs per year, as not all dwellings are reported every year (e.g. one can have 2 records whereas another one can have all five). Table 1.2 presents the exact numbers.

TABLE 1.2 Number of dwellings reported in SHAERE per year

YEAR OF REPORTING	AMOUNT OF INDIVIDUAL DWELLINGS REPORTED	PERCENTAGE OF THE TOTAL NON-PROFIT STOCK
2010	1,132,946	47.2%
2011	1,186,067	49.4%
2012	1,438,700	59.9%
2013	1,448,266	60.3%
2014	1,729,966	73.7%

5 The theoretical energy consumption is calculated according to the ISSO 82.3 norm (ISSO 2009)

In this thesis, the Dutch EI will be examined through consecutive years in order to calculate the energy renovation rate based on the energy performance of the dwellings (Chapter 3). The EI is the official coefficient for measuring the energy efficiency of an existing dwelling, and is often categorised into an energy label, ranging from A to G (see Table 1.3).

The EI is related to the total theoretical energy consumption of a building or a dwelling: Q_{total}. According to the norm of the calculation of the EI, as shown in Equation 1.1, it is corrected taking into account the floor area of the dwelling and the corresponding heat transmission areas.

The EI is calculated as follows:

$$EI = \frac{Q_{total}}{(155 * A_{floor} + 106 * A_{loss} + 9560)} \qquad \text{Equation 1.1}$$

Q_{total} refers to the modelled characteristic yearly primary energy use of a dwelling, and includes energy for space heating, domestic hot water, additional energy (auxiliary electric energy needed to operate the heating system, i.e., pumps and funs), lighting of communal areas, energy generation by photovoltaic systems, and energy generation by combined heat and power systems under the assumption of a standard use (Filippidou et al. 2016; Visscher et al. 2012; ISSO 2009). A_{floor} refers to the total heated floor area of the dwelling, whereas A_{loss} refers to the transmission heat loss are in the dwelling, such as a cellar (Filippidou et al. 2016; Visscher et al. 2012; ISSO 2009). The numerical values in the denominator are: 155 is the factor for the reference energy consumption per m^2 correction, regarding the useful living area (MJ/m^2); 106 is the correction factor compensating for the transmission losses (MJ/m^2); and 9560 is a standard amount of energy used for existing dwellings (MJ) (NEN 2012).

TABLE 1.3 Connection of Energy Index with the Energy Label in the Dutch context and the primary heating energy consumption (ISSO, 2009)

ENERGY LABEL	ENERGY INDEX	MEAN THEORETICAL PRIMARY HEATING ENERGY CONSUMPTION ($kWh/M^2/YEAR$) (MAJCEN ET AL., 2013)
A (A+, A++)	<1.05	96.8
B	1.06 – 1.3	132.5
C	1.31 - 1.6	161.6
D	1.61 - 2.0	207.8
E	2.01 - 2.4	265.0
F	2.41 - 2.9	328.0
G	> 2.9	426.9

The main focus of the thesis is on the dwellings that have been reported more than once (i.e. where data have been inputted by the housing associations in repeated years) in order to pinpoint and research the energy improvements performed each year. We use longitudinal data to observe the changes of the energy performance of the same dwellings. We observe whether or not the inputted data have changed from 2010 to 2014. We start with the changes in the EI and we move on to thermo-physical variables.

We develop an inventory of ESMs (Energy Saving Measures) of the non-profit rented stock in Netherlands from 2010 to 2014.We examined the effectiveness of these measures based on actual and predicted energy savings as annual values between 2010 and 2014. We connect the data from the SHAERE monitoring system to the actual heating energy consumption data from Statistics Netherlands on a dwelling level. Using longitudinal analysis methods we are able to identify the energy efficiency improvements of the stock and to determine the effectiveness of different measures in terms of actual energy savings.

However, the estimation of future renovation rates is of great importance and can assist in future energy efficiency policies. To that end, we applied the dynamic dwelling stock model for the non-profit housing stock and then compared the projected renovation rates with the results of the statistical analysis using SHAERE database. As a result, we predict the energy renovation rates in the Netherlands using dynamic building stock modelling and statistical regression analysis. The dynamic dwelling stock model aims at describing the long-term development over time of the size and age composition of the dwelling stock in a country or region, in this case the social housing stock of the Netherlands (Sandberg et al. 2016 & Sartori et al. 2016). The statistical data analysis approach is using SHAERE database and the energy renovation rates of several parameters. Figure 1.5 summarizes, the relationship of methods, data and their presentation through the chapters of the thesis.

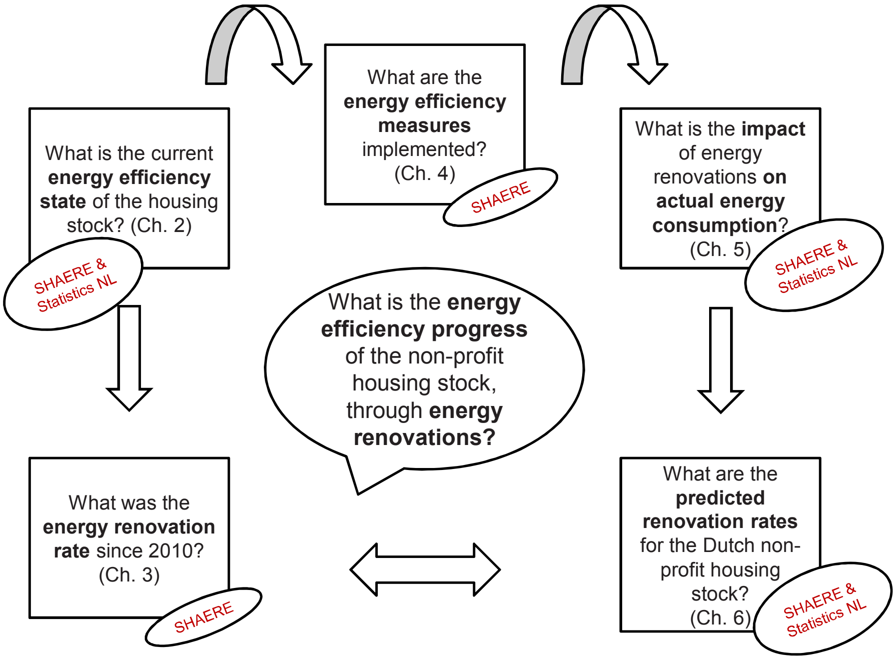

FIGURE 1.5 Thesis connection of research questions and data used

§ 1.7 Limitations

When it comes to research for energy renovations in the built environment, dynamic databases using time series data prove to be extremely useful. Longitudinal data are very important to follow the actual energy performance of housing stocks. Datasets and monitoring systems with detailed information, like SHAERE or EPC (Energy Performance Certificate) databases, prove to be extremely useful to evaluate policies, project future renovation rates and conclude on best practices for different housing stocks (Brøgger & Wittchen 2017; Hamilton et al. 2017; Dascalaki et al. 2016; Droutsa et al. 2016; Corrado & Balarini 2016; Serghides at al. 2016; Stein et al. 2016). One of the strengths of SHAERE is the very large amount of data (more than 50% response rate each year), which is more than half of the dwellings of the non-profit housing sector in the Netherlands. The large dataset is important since the study aimed at calculating the energy improvement pace of the sector. In this sense, the monitoring system can set an example for the rest of the housing sectors. SHAERE has proven to be a rich database on the energy performance of the non-profit sector.

This research was based on the dwellings' physical properties and the reported heating energy consumption, in order to examine the improvements and pace of energy renovations. Concerning the quality of the data used and the impact on the results of this study, two points should be mentioned. First, we cannot be completely confident about the quality of the inspections taking place in the sector. As a result, concerns have been raised about accuracy of the input data in SHAERE. Although there has not yet been a study regarding the quality of SHAERE, a series of studies carried out by the Inspection Service of Ministry of Housing, for the official energy labels database of the Netherlands, reported that in a sample of 120 labels issued in 2009, 60.8% of the inspected labelled dwellings had an EI that deviated more than 8% (Majcen et al. 2013a; VROM-Inspectie 2009). In 2010, only 26.7% had a different EI (VROM-Inspectie 2010) and in 2011, 16.7% of labels deviated more than 8% in their EI (VROM-Inspectie 2011). In 2013, the inspection was carried out only for office buildings. Hence, there seems to be a trend of improvement, although the studied samples are small (Majcen et al., 2013a). Further research is required to determine the amount of wrongly reported values of dwellings. We recommend that input methods be tested and validated in future monitoring systems.

In SHAERE, data with regard to a new reference date are 'simply' added as new records to the existing dataset, meaning that the database must first be restructured to connect the information about a dwelling with regard to several reference dates (Stein et al. 2016; Filippidou & Nieboer 2014). This is a time-consuming procedure which had to be repeated every year. The situation is exacerbated by the fact that individual dwellings do not have an own ID, where data regarding different reference dates could be coupled (Stein et al. 2016; Filippidou & Nieboer 2014). So far, and for this thesis, this was done by creating an encrypted ID variable based on address information (postal codes, street numbers and possible extensions), but although the Dutch postal codes are very refined (on sub-street level), this method is still less reliable than an individual ID. As a result, in future monitoring systems we recommend the use of a unique ID for dwellings from the beginning of the system.

The monitor could be further improved if it contained data on a possible renovation: is the dwelling renovated and, if so, in which year. Until the 1990s, renovations in the non-profit housing sector were subsidised by the national government. Because of this, and because this type of interventions is relevant for today's asset management, there is good chance that housing associations still have this data available (Stein et al. 2016). A pilot would have to be carried out to check this and its applicability.

§ 1.8 Added value of the research

§ 1.8.1 Scientific contribution

Many studies focus on the impact of the built environment, and more specifically the residential sector, on the total heating energy consumption and how it can be improved. Previous research has focused on the impact of building components, occupants and different socio-economic factors, including the implementation of policies, on the energy performance of buildings or residential dwellings (van den Brom et al. 2018; Rasooli et al. 2016; Majcen et al. 2016; Majcen et al. 2013; Santin et al. 2009) . The availability of large datasets, during the last decade, has laid the groundwork for empirical evidence on the development of the energy efficiency of building stocks. Despite this, the limited availability of detailed empirical data on the energy demand of dwellings complicates our understanding of the impact of technologies used (e.g. energy installations) and policies applied (Hamilton et al. 2017).

The objectives of this work, are focused on crucial elements of the energy renovation and efficiency processes to fill in the gap in literature of what is the impact of state-of-the-art measures of dwellings in the non-profit housing stock. Research on the energy renovations of dwellings usually focuses on selected cases (exemplary buildings) or case studies (Khoury et al. 2016; Mastrucci et al. 2014) except for a few dealing with epidemiological methods (Hamilton et al. 2017). Up to now, and due to the difficulty of acquiring actual heating energy consumption data on big datasets much of the research performed focused on the predicted energy savings of renovated building stocks (Ballarini et al. 2014; Mata et al. 2013). The ability to track renovations of a dwelling stock heavily relies on data availability. For this research, we were able to work with SHAERE and Statistics Netherlands longitudinal data. We start by introducing the energy efficiency state of the non-profit housing stock in the Netherlands and we then move in to examine how fast is this stock being renovated the last years. We then analyse which were the energy saving measures implemented and what is the most efficient way to determine which sets of measures would be more beneficial based on predicted and actual heating energy consumption.

At the same time, international comparisons on the energy refurbishment processes and efficiency measures of the housings stocks between countries and different refurbishments processes are important to understand the methods and approaches used in research. The comparisons were implemented through the IEE (Intelligent Energy Europe) of the EU programme EPISCOPE. Energy monitoring and future energy renovation scenario indicators were developed. This resulted in the special issue journal publication “Towards an energy efficient European housing stock: Monitoring, mapping and modelling retrofitting processes”(Visscher et al. 2016) and a comparison of the energy renovation rates of 11 EU countries publication that can be found in Appendix B(Sandberg et al. 2016). The non-profit housing stock of the Netherlands and the results on the energy renovation pace and the energy efficiency state were examined according to the dwellings typology (age, type, characteristics), as part of the EPISCOPE project and through the collaboration with NTNU (Norwegian University of Science and Technology) for the prediction of renovation rates (Chapter 6).

§ 1.8.2 Societal contribution

The application and societal impact of every research is the core driving force for its completion. The way the research outcomes are applied in the real world is of great importance. In addition to the quantitative research of the renovation pace and process of the housing stock, the results of this research provide an insight as to which types of energy renovations create the strongest impact regarding energy efficiency. They provide a link to the qualitative data that are assessed relating to the explanation of the renovation pace process and the energy saving measures.

As stated in the start of this sub-section one of the goals of every research performed is to be of use to several sectors and stakeholders involved. Apart from the goal to add something to the combined effort of the Netherlands and the EU for the targets set in improving the energy efficiency of the residential sector, there is a need to provide information and work with the non-profit rented housing organizations. Answers to questions like which are the most efficient energy renovation solutions for the Dutch non-profit housing benefit the housing organizations and as a result the tenants of the dwellings as well.

The outcomes of this work can be critical and useful to the entity of the stakeholders involved in the housing sector and especially the social housing. From the organizations managing the stock, to the occupants living in the houses, the neighbourhoods and how they deal with the energy efficiency aspect of their homes to governmental authorities that will create policies and measures towards this path, we tried to provide clear and useful results that can be of use to the majority of the aforementioned stakeholders.

§ 1.9 Structure of thesis

This study contains five components that support its main goal to discover how achievable energy neutrality is in the built environment. In order to answer the main question, first we need to understand the current energy efficiency state of the non-profit housing stock, as presented in **Chapter 2**. We examine the efficiency of the stock in 2015 in terms of descriptive statistics of the main elements of the thermo-physical and dwelling characteristics. These include the age, type, useful floor area, thermal resistance (R_c-value) of the envelope (roof, facades and floor), thermal transmittance (U-value) of the windows, heating and domestic hot water (DHW) systems, ventilation system and energy production systems, if present.

In **Chapter 3**, the energy renovation pace for the non-profit housing stock of the Netherlands is introduced, based on the changes in the energy performance of about 800.000 dwellings for the period of 2010 to 2014. We identify the number of dwellings in the non-profit housing sector that showed an improved energy performance during the period of 2010-2014, and then compare it to the non-renovated sample of dwellings. Moreover, we also analyse the energy improvements of the stock per year to get a more detailed view and assess the trend of the energy renovation pace.

However, to get a better picture of the energy renovations applied in the sector, a thorough examination of the renovation measures is necessary. In **Chapter 4**, we identify the specific energy efficiency measures that have been realised between 2010 and 2013. In order to assess the effect of the measures on energy performance, an analysis of the changes in the energy systems and envelope elements of the dwellings is presented.

Usually, the energy savings are based on modelling calculations. However, in **Chapter 5,** we re-assess the effectiveness of energy measures based on actual consumption data. We examine the impact of thermal renovation measures on both the predicted and the actual heating energy consumption of the renovated non-profit stock in the Netherlands. Actual savings not only reveal the true effect of renovations on the reduction of heating energy consumption but they also highlight the impact of the number and combinations of measures on the dwellings' performance. Consequently, we address the gap between predicted and actual energy savings and its impact on regulations and policies concerning the energy efficiency of the built environment.

So far, we have analysed the energy efficiency state of the non-profit housing stock and the energy renovations that have taken place since 2010. Having a clear picture of the present and past is essential for the prediction of future renovations and the evolution of the housing stock. Despite common efforts, throughout Europe, national approaches to monitor the building stock have evolved separately. Information about the progress of the energy renovations is required to track the progress of policy implementation. To address the shortcomings and challenges identified, there is a need for a new methodology that can be used for consistent and scalable analysis of building stock across multiple countries. For this reason, in **Chapter 6,** we provide insight into the future renovation rates of the Dutch non-profit housing stock, using two different methods. First, based on the empirical data of SHAERE, we use regression forecasting to show at which rate renovations must happen to reach energy neutrality. Then, we apply the dynamic dwelling stock model developed in NTNU ("Norges Teknisk-Naturvitenskapelige Universitet" – in English: Norwegian University of Science and Technology) to compare the renovation rates and reach conclusions regarding the ways in which energy neutrality in the building stock can be achieved. The application of the dynamic model is the result of a fruitful collaboration with the Industrial Ecology group in NTNU and a month-long visit in Trondheim, Norway.

Chapter 7 completes this study. The findings of this thesis are brought together to draw general conclusions. Moreover, the limitations of the study, the contributions to both policy and practice, and recommendations for future research are discussed.

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